UNIVERSITY OF COLORADO
BOULDER, COLORADO

DEPARTMENT OF PHYSICS AND ASTROPHYSICS

February 8, 1965

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Project Coordinator: L. M. Branscomb
Joint Institute for Laboratory
Astrophysics, Tel. 443-8610
Boulder, Colorado

Director, Advanced Research Projects Agency (3)
Box CM, Duke Station
Durham, North Carolina

Information Processing Office (3)
Box CM, Duke Station
Durham, North Carolina

Gentlemen:

The individual efforts under this contract during the period October 1, 1964 through December 3 1964 are as follows. This report is organized according to the way we have set up our projects at C. U.

1. Plasma Statistics. (Dr. Brittin and Dr. Sakakura)

Field theoretic methods are being applied to many body problems including the interaction between particles and radiation in a plasma. Both equilibrium phenomena and transport phenomena have been considered.

The equilibrium properties of the electron gas as well as bose gases are being investigated using generalized linked cluster expansions. It is hoped that these methods can be extended to non-equilibrium problems.

Theories of transport in a nearly homogeneous plasma have been developed*. A hierarchy of equations has been established which couples various particle

*Supported in part by Aerospace Research Laboratories, Office of Aerospace Research, United States Air Force, Wright Patterson Air Force Base, Ohio.

and photon distribution functions. This hierarchy is similar to, but different in structure from, the usual BBGKY hierarchy for statistical mechanics of interacting particles. The hierarchy is truncated by the use a superposition ansatz which relates higher order correlations to lower order correlations and lower order distribution functions. The method of Bogoliubov is used to solve approximately the resulting closed set of coupled equations. There results a set of equations which relate to macroscopic processes of irreversible phenomenon. Terms in these equations correspond to various physical processes such as electron-electron scattering, Thompson scattering and bremsstrahlung. In addition there occur some terms which are intuitively unexpected. Such terms are found to be quantum-mechanical in nature and correspond to energy-momentum conservation in intermediate states. These terms cannot occur in isolated two particle bremsstrahlung and must be regarded as many body effects. Similar effects have been observed by the French physicist, A. Mangeney*. An analysis of these non-overall two-body energy-momentum conserving processes has been carried out along the following lines:

There are two generally used methods for deriving kinetic equations (master equations, or gain-loss equations) one of which may be called the "guessing method" and the other the rigorous method. The rigorous method starts with the Liouville equation or the quantum-mechanical analogue and then proceeds by rather well defined mathematical procedures and assumptions to establish macroscopic equations. The "guessing method" starts with a Pauli type master equation and proceeds by the use of two-body perturbative methods for transi-

*A. Mangeney - Physica 30, 461 (1964)

tion rates. It is shown that changing the order of certain limiting processes in perturbation theory leads to transition rates in agreement with the unexpected terms.

A macroscopic quantum electrodynamic theory has been applied to plasmas. This theory leads to a deeper understanding of "dressed" or quasi-photons.

Work is being continued along the above mentioned lines, and in addition the fundamental problems of statistical mechanics of field is being investigated.

2. Aerodynamics. (Dr. M. S. Uberoi)

Double Diaphragm Combustion Driven Shock Tube (T. G. Jones): Preliminary experiments are in progress to investigate the performance of a fast response pressure transducer[1] which is to be used in experiments on overdriven detonations. Current results indicate that this gauge is capable of recording pressures for a time of 5μs with a response time of less than 0.2μs. Work is now in progress to determine whether this gauge gives a faithful response to the theoretically predicted Von-Neumann peak pressure in hydrogen-oxygen detonations. Because of the predicted high value of this peak pressure and also the rapid decay to the equilibrium pressure (~ 10 ARM in 0.1μs), experimental measurements have been impossible. Present results, however, indicate that the peak pressure is recorded. Further work is required in order to determine the linearity of the gauge and also its response to a pressure disturbance that does not exhibit a sharp peak, for example, a non-reactive

(1)D. Baganoff, Pressure Gauge with One-Tenth Microsecond Rise-time for Shock Reflection Studies, The Review of Scientific Instruments, 35, 3 March 1963.

shock wave.

Cesium Plasma Experiment (C. Forbes Dewey, Jr.): The 10 kilogauss magnet and 60 kilowatt D.C. power supply have finally been received from the manufacturer. The magnet has been installed on a movable tract to facilitate access to the plasma generators located within the magnetic field. Four 1" diameter holes spaced 90° apart extend radially through the magnet and focus on a common axial location. These holes have been designed for microwave and laser experiments on the plasma.

An analysis of the flow of a plasma through a porous medium has been completed. It indicates that the percentage of neutrals in the gas phase decreases drastically with increasing temperature, and at temperatures sufficient to provide significant thermionic emission, the gaseous plasma is nearly fully ionized.

Further development of porous tungsten-tantalum alloys has been pursued. This work, as well as the plasma flow analysis, will be published shortly. It may be stated that the density, pore size, and composition of the tungsten-tantalum alloys may be tailored to meet specific requirements. 70% W - 30% Ta discs with 70% theoretical density and 50-micron pores will be used in this experiment.

Inverse Pinch Shock Tube Project (G. C. Vlases):

During the period September-December 1964, the Inverse Pinch Machine has been operated with a variety of gases (Air, Helium, and Hydrogen) over a pressure range of from 50μ to 500μ Hg, without an external magnetic field.

A spark gap switch capable of handling the peak currents of 600,000 amps encountered in these experiments has been developed to the point where it now operates quite reliably for several hundred shots without requiring attention.

These preliminary experiments show that the ideal "snow-plow" velocity is achieved at high pressures in heavy gases, but that the agreement between measured and calculated velocities becomes progressively poorer as molecular weight and pressure are decreased. This is believed to be a result of two causes: the use of a larger diameter center conductor than has been used previously, in order to minimize inductance; and poor breakdown characteristics caused by operating below the minimum in the Paschen breakdown curve.

A new chamber has been put into operation. It utilizes a smaller diameter center conductor and glass top and bottom plate "electrodes". These have been shown to give cleaner, more reproducible discharges, and also permit the establishment of a pulsed axial field within the chamber. The capacitor bank and switching circuits for this axial field are essentially complete and will be put into operation shortly.

Two graduate students have been developing diagnostic techniques. One of them has completed the instrumentation for a sensitive Doppler shift measuring device. The other one is working on the laser interferometer. These will augment the pressure probes, magnetic probes, image converter camera, and time-resolving spectrometer which are already in use.

3. Astrophysics (Dr. J. Cox)

The paper, "Equilibrium Models for Helium Burning Stars. III. Semi-Degenerate Stars of Small Mass", by J. P. Cox and E. E. Salpeter, was published

in the August 15, 1964 issue of the Astrophysical Journal. A review by J. P. Cox of the book, Basic Astronomical Data, edited by K. A. Strand, was published in the November, 1964, issue of the Bulletin of the American Metrological Society.

Collaborative effort of non-linear stellar pulsations involving J. Cox and the Los Alamos Group (A. N. Cox, et al) continues, and recent results are being analyzed by David S. King of Indiana University in connection with a Ph.D. thesis. A series of three papers covering this work is now in preparation.

Considerable progress has been made on the book originally entitled Stellar Structure and Evolution (present tentative title: Stellar Structure) by J. Cox in collaboration with R. T. Giuli. A typescript of the present draft is now (1-4-65) about three-eights completed.

A paper and a note concerning properties and evolution of helium stars is being prepared for submission to the Astrophysical Journal by T. Neil Divine (a JILA postdoctoral research associate). Dr. Divine is continuing with further calculations along these lines.

A note, "Possible Implications of the Observed Profile of [λ 6374] Fe X", by C. Pecker-Wimel and R. N. Thomas, has been submitted to the Astrophysical Journal for publication.

Calculations pertaining to convective motions in the solar atmosphere are being carried out by G. McHugh.

A JILA Report, "Acrodynamical Phenomena in Stellar Atmospheres - Supplementary Bibliography Covering the Period 1960-64", has been prepared by S. Jordan in collaboration with S. A. Kaplan and S. B. Picklner.

A. Hearn has continued the calculations started at the U.R.A.E.A. Culham Laboratory on the line intensities emitted by an optically thick hydrogen-like ion plasma in a steady state. The calculations are an extension of the optically thin calculations of McWhirter and Hearn and include the effect of photo-excitation and stimulated emission in the emission lines.

J. Oxenius has been studying the relation between irreversible thermodynamics and radiative transfer.

Some machine computations of stellar convective envelopes of M. S. Vardya have been supported by ARPA funds.

4. Atomic Theory and Spectroscopy (Dr. Edward Condon)

Collaborating on this phase of the work are Dr. R. N. Zare, Research Associate, and Miss Janet Stober, Research Assistant.

Through the courtesy of Dr. Frank Herman of Lockheed Missiles and Space Company, the program for Hartree-Fock calculations of the type presented in the book of Herman and Skillman [Atomic Structure Calculations, Prentice-Hall 1963] has been obtained. Programs have been written locally for calculation of the radial integrals of electrostatic interaction with any set of radial functions. This puts us in good position to make a fully detailed comparison of the theory of complex atoms with the observed energy levels.

Attention has been concentrated at first on a new calculation of configuration interaction of the $3p^2$ and 3s3d configurations in the magnesium (Z=12) isoelectronic sequence. Historically this is the oldest example of configuration interaction [Condon & Shortley, Theory of Atomic Spectra, p. 366] but the early work of R. F. Bacher was confined to magnesium and was done with crude approximations to the wave functions.

The remarkable thing is that $3p^2$ lies high, at the Mg II ionization limit in Mg. I, and pushes the 3snd ^1D terms down below the ^3D terms, but in Al II and higher members the $3p^2$ lies very much lower, almost at the same energy as the 3s3d configuration, so that configuration interaction effects are even greater. This shift in the relative positions of $3p^2$ and 3s3d between Mg. I and Al II are so great as to cast some doubt on the correctness of the empirical spectral analysis. Remarkably, the Hartree-Fock calculations reproduce this effect in detail, confirming the analysis and showing greater mutual perturbations of the ^1D terms in Al II, and Si III, than are shown in Mg. I.

Some calculations of E. Trefftz [Zerschrift fur Astrophysik 26, 240 (1949)] show the effects of such configuration interaction on transition probabilities in Mg. I. It is planned to revise these with the improved wave functions now available and to extend them also to Al II, Si III and P IV for which the results will also find astrophysical application, as well as in Mg. I.

5. Atomic Collisions (Dr. Gordon Dunn)

Lyman-α: Attempts to obtain high quality measurements of the excitation of the 2P state of atomic hydrogen were continued. The Lyman-α detector was

repaired and improved to reduce photoelectric effect from visible light. Various control schemes to achieve pressure stability in the hydrogen dissociator were tested. Data was obtained for 2P excitation at a range of electron energies up to 200 eV. This data appears to be internally consistent and has a small statistical spread. This data differs markedly from previous theoretical and experimental results, and further data runs are planned to include more energy points as well as to demonstrate the reliability of the experimental design. These runs will be designed to show up any effects of small changes in electron beam geometry, which is considered to be the most critical problem.

Double-Quantum Photodetachment of I^-: Work to measure the double quantum photodetachment probability of the negative ion of atomic iodine has begun. Ions processing kinetic energy of 500 eV are passed through the beam of a Q-switched ruby laser, and the current of ejected electrons measured. The ruby photon energy is smaller than the iodine electron affinity, so that single photon detachments are forbidden. Two quantum detachment is energetically possible to detect for high enough light intensity. Geltman[1], using second-order perturbation theory with a summation over virtual intermediate R states, has calculated an approximate value of $(.5 \times 10^{-50} \bar{F}^{-2})$ sec^{-1}, where $\bar{F}$ is the photon flux in photons $1cm^2$-sec, for the double quantum detachment possibility.

The effect has apparently been observed during a crude preliminary set of runs, but without the necessary knowledge of either light or ion beam

(1) S. Geltman, Physics Letters, 4, 168 (1963).

characteristics to permit quantitative observation to be made, although the electron signal has order-of-magnitude agreement with Geltman's calculations.

The apparatus is currently being modified to permit accurate measurements of the ion current density and photon flux in the interaction region.

Isotope effect: To gain some possible insight into the reasons for the isotope effect observed in double stripping of H^- and D^- and discussed in earlier reports, a Fortran program was written to calculate in Born approximation the cross section for the ionization of H by heavy particles. The object of this program was to see if there is a mass dependence for this cross-section near threshold. Calculations are now in progress.

Electron - H^- Collisions: To prepare for the measurement of the cross section for detachment of electrons from H^- by electrons, a neutral particle detector was designed, and construction has begun. The necessary changes in the existing cross beam apparatus to do this experiment are being designed.

Metastable Atomic Collisions: In the past three months an apparatus was designed for the detection of long-lived excited states of molecules and for the study of ionizing collisions of polyatomic molecules with metastable atoms. It is under construction in the JILA shop and will be finished in January.

In the first period of the work the molecules of astrophysical interest, H_2, N_2CO, O_2, NO, N_2O, CO_2, SO_2 and simple polyatomic molecules CH_4, C_2H_2 and C_2H_4 will be used and their long-lived excited states will be detected by the ionization of molecules with appropriate ionization potential.

In the second period the kinetic energy of released electrons in the collision of the second kind will be measured by retarding potential method and the distribution of excitation energy of molecular ions will be determined.

Dissociative Ionization Cross Sections: This quarter some improvements in the vacuum system have been made. These changes should significantly improve the performance of the vacuum system and greatly reduce down time. These improvements have essentially been completed and next quarter some data on the angular distribution of fragments from the dissociative ionization of D_2 will be taken.

6. Atomic Resonance (Dr. J. Hall)

The lifetime of the $4_P\ ^2P_{3/2}$ state of Ca II is being measured by Drs. W. Smith and A. Gallagher using the Hanle-effect technique. The exciting resonance radiation is produced with a flow lamp(1), and the scattering ions are produced by injecting calcium into an argon discharge. In order to minimize collisional influences as well as to reduce background light from the discharge, the discharge is operated in a pulsed mode and the scattered resonance radiation detected while the discharge is off. Multiple-scattering narrowing and Argon collision broadening of the line have been evaluated, and can be eliminated at appropriate operating conditions. A preliminary value of $64 \pm 5 \times 10^{-9}$ sec. has been obtained for the lifetime.

(1)Columbia Radiation Laboratory QPR(Dec. 16, 1961 to March 15, 1962)

7. Information Center (Dr. Lee Kieffer)

This past quarter the JILA Information Center has continued to give support to the preparation of a critical review of ionization cross section

data for atoms and diatomic molecules. This was discussed in the last quarterly report.

The low energy atomic collision bibliography and collection of reprints is being kept up to date. A reviewed "Bibliography of Low Energy Electron Collision Cross Section Data" (This was first issued as JILA Report #4, NBS Report 7993, January 1, 1964) is being prepared and expected to be issued in February 1965.

Work has begun on writing a machine language program (for use on the University of Colorado IBM 709 computer) for generating a magnetic tape which will store all of our general bibliographic information. Parts of the program are already written and it is expected that the program will be complete and running on the machine by some time during the next quarter.

8. Spectroscopic Theory (Dr. R. H. Garstang)

A program of calculations of atomic oscillator strengths has been initiated. This work is directed towards the ultimate goal of enabling improved determinations of the physical conditions in laboratory and astrophysical plasmas to be made. One atom which is under study is neutral argon. There has been an increasing interest in the study of discharges in argon in the laboratory, and an improved theoretical basis would help in understanding the physical processes involved in the discharges. The spectrum of argon shows considerable departures from the usual Russell Saunders coupling theory, and one would, therefore, expect that theoretical calculations based on this theory would be very inadequate. Accordingly, detailed intermediate coupling theoretical calculations have been undertaken. The energy levels of the argon spectrum are

well known, and these are used as the basic data in the calculations, for determining the parameters of the theory. Calculations have been completed for the red group of lines in the argon spectrum, and work is in progress on the blue group of lines. One possible check on the calculations is provided by th Lande g-factors, and for the energy levels giving the red group of lines the agreement of the g-factors is good. The oscillator strengths and transition possibilities which have so far been obtained are in fairly good agreement with the results for shock tube experiments and for discharges. Results have also been obtained for a number of spectral lines which had not previously been studied.

A second atom which is under study is singly ionized silicon. This ion has been studied in the laboratory, under difficult circumstances, and the available data is nowhere near enough for astrophysical applications. Si II occurs in the visible and in the ultraviolet solar spectrum. Si II is also present in many stellar spectra, where it is of particular interest, in the case of some of the hotter stars, because it is present along with Si III and even Si IV. One important quantum mechanical effect has been neglected in many calculations, namely configuration interaction. It turns out that for many ions the neglected effects are important. One suchcase is Si II. Here there are two terms, arising from the configuration $3s3p^2\,{}^2D$ and $3s^2 3d\ {}^2D$, which interact very strongly, and even a very crude theory is all that is needed to demonstrate the presence of the interaction between the two terms. One can indeed reverse the approach, and estimate the interaction from the observed spectrum without the necessity for elaborate calculations of atomic wave functions. Work is now in progress to calculate the effect of the interaction of the strengths of

the spectral lines connecting these two terms, and others, with the ground state and several excited states of the ion. Preliminary examination of the problem shows that the calculations will give results for several well observed lines of Si II which have a zero probability on the usual theory which neglects configuration interaction.

Examination has also begun of the validity of the f-sum rule for complex spectra. The theory on which the sum rule is based ignores the Pauli exclusion principle. Thus the f-sum should be extended to include certain (downward) transitions which are forbidden in a real atom but which are not excluded in the theory. Stated in another way, a correction should be applied to the theoretical sum before it is applied to the real observable transitions in an atom. This has almost never been done. The forbidden transitions cannot be observed in the laboratory, and only theoretical calculations can give the desired information. It is hoped to study many atoms of the iron group in due course; for a pilot calculation neutral chromium has been selected, and a calculation is now in progress of the atomic wave function for an electron in a forbidden state.

9. Reaction Rates (Dr. Earl Beaty)

Dr. S. B. Woo is putting together a Paul-quadrupole-type mass spectrometer. The spectrometer will be used to assist in the identification of negative ions in high pressure oxygen. A measurement with positive identification is sought for the mobility of O_2^-. The quadrupole and supports were supplied to the project by NBS.

Studies of the mobilities of negative ions from a pulsed discharge are continuing. Present data suggests the presence of an impurity ion which has a mobility close to that of O_2^-. A careful assembly of mobility data is in progress. A measurement of the attachment rate for electrons is planned. Such a measurement will include a determination of the mobility of the end product. This attachment data combined with ion reaction rate studies should provide a unique identification of the various mobilities. The mass spectrometer is intended to remove all doubt about identity.

Analysis of reaction rate data on oxygen negative ions is proceeding. The diffusion coefficients are found to be anomalously large. The computer program is being modified to permit more flexibility in the treatment of diffusion coefficient.

Mr. Paul Patterson is constructing an apparatus for the determination of the temperature dependence of the mobility of He and He_2^+ in helium.

10. Consultants, Administration, Equipment and Reserve (L.M. Branscomb)

During this quarter the following colloquium speakers and lecturers contributed to our program through their participation in our Colloquium Series and by discussions with our staff:

Dr. Dimitri Mihalas (10-12-64) Department of Astronomy, Princeton Astronomical Observatory "The Temperature Structure of Stellar Atmospheres"

Dr. R. P. Madden (12-1-64) National Bureau of Standards, Washington "Autoionizing Phenomena in Ultraviolet Spectroscopy"

Dr. W. Fairbank (12-2-64) Department of Physics and Astrophysics Stanford University "Fundamental Experiments Using Low Temperatures"

Dr. James M. Peek (12-8-64) Sandia Corporation, Albuquerque, New Mexico "The Dissociation of the Hydrogen Molecule Ion During Fast Collision"

Dr. W. B. Thompson (12-11-64) Oxford University, Oxford, England "Non-Linear Wave Interaction in Plasmas"

MANUSCRIPTS INVOLVING ARPA FUNDS

W. R. Chappell and R. J. Swenson, "Guessing kinetic equations," submitted to Physical Review Letters.

S. Jordan, S. A. Kaplan, and S. B. Pickelner, eds., "Aerodynamic phemonena in stellar atmospheres - supplementary bibliography covering the period 1960-64," JILA Report No. 25, December 2, 1964 (unpublished).

K. Takayanagi and S. Geltman, "Excitation of molecular rotation by slow electrons," Phys. Lett. 13, 135 (1964); an expanded version of this paper has been submitted to the Physical Review.

A. Gallagher and W. W. Smith, "Hanle effect in the $4^2P_{3/2}$ state of ionized calcium," submitted to Bulletin of the American Physical Society. [Talk to be given at the Washington Meeting of the A.P.S., April 26-29, 1965.]

Yours very truly,

Lewis M. Branscomb
Project Coordinator

cc: Battelle Memorial Institute
505 King Avenue
Columbus 1, Ohio
Attn: Battelle - DEFENDER

ESTIMATED EXPENDITURES TO DATE

PROJECTS	EXPENDITURES	OBLIGATION	TOTAL
General Astrophysics	$ 30,099.55	$	$ 30,099.55
Plasma Statistics	28,430.01		28,430.01
Aerodynamics	170,196.11	40,117.00	210,313.11
Astrophysics	49,326.54	5,867.43	55,193.97
Atomic Theory	71,716.47	13,493.04	85,209.51
Atomic Collisions	51,830.64	3,622.00	55,452.64
Atomic Resonance	30,643.37	6,130.00	36,773.37
Ultraviolet Spectroscopy	2,842.45		2,842.45
Data Center	23,301.43		23,301.43
Spectroscopic Theory	1,451.10		1,451.10
Reaction Rates	11,956.61	50.00	12,006.61
TOTAL	$471,794.28	$69,279.47	$ 541,073.75
Available Funds			1,845,000.00
TOTAL REMAINING FUNDS			$1,303,926.25